Tunable red-light source by frequency mixing from dual band Er/Yb co-doped fiber laser

Johan Boullet, Laure Lavoute, Agnès Desfarges-Berthelemot, Vincent Kermène, Philippe Roy, Vincent Couderc, Bernard Dussardier, Anne-Marie Jurdyc

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J. Boullet, L. Lavoute, A. Desfarges Berthelemot, V. Kermène, P. Roy, V. Couderc
Xlim, Département photonique, UMR CNRS n°6172, 123 Avenue A. Thomas, 87060 Limoges
johan.boullet@xlim.fr

Bernard Dussardier
LPMC/FOA, Université de Nice Sophia-Antipolis, Parc Valrose, 06108 Nice, France

Anne-Marie Jurdyc
LPCML, Bât A. Kastler 10 rue A.M. Ampère 69622 Villeurbanne Cedex

Abstract: We report an all solid state laser device producing tunable dual wavelength emission in the near IR region (1060nm, and 1550 nm) by use of an Er/Yb co-doped fiber. Generation of continuous-wave radiation around 630 nm is then demonstrated by extra-cavity sum frequency mixing in a Periodically Poled Lithium Niobate (PPLN) crystal. Quasi phase matching conditions are obtained over 7 nm to generate tunable coherent light in the red spectral range.

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1. Introduction

Interest for compact multiwavelength coherent light sources in the visible and near infrared regions considerably increased these last years because they are key components for many emergent applications in biophotonic area such as fluorescence analysis, or Coherent Anti-stokes Raman Scattering (CARS) microscopy.

Up to now, the main efforts to obtain multiwavelength emission in visible and near infrared regions consist in generating supercontinuum by use of microstructured fibers. In this concept, the spectral power density obtained after the nonlinear spectral broadening is usually low because of the limited energy carried by the input pump pulse. A new promising method to avoid this problem could be the multiwavelength generation from a multi-doped fiber combined with a tunable Sum Frequency Generation (SFG) in a non linear medium.

Several processes have been studied in the past few years to obtain a compact two-color laser source in the near infrared region before reaching the visible spectrum by SFG. Up to now, the two-color laser sources are often based on cascading nonlinear Raman effect either in bulk media such as $NdYAlO_3$ [1] or $KGd(WO_4)_2$ [2] or in optical fiber [3]. But the generation of several Stokes orders in Raman laser is limited by the discrete number of produced wavelengths. Moreover, the broad linewidth of the Raman laser frequencies (higher than the spectral acceptance of the non linear crystals) forbids efficient wavelength conversion using second order nonlinearity [3]. Some experiments have also shown the simultaneous oscillation of two lasing lines from a single laser crystal ($Nd:GdVO_4$, Nd:YLF) [4,5]. In that case, the dual emission requires a fine adjustment of the Q cavity factor at each wavelength to optimize the gain competition. Another way to make a two-color laser is based on the use of a common cavity including in line both Er and Yb fibers [6]. This geometry has the particularity to avoid gain competition between the oscillating wavelengths. In order to increase compactness and simplicity of the device, another approach consists in combining different rare earth ions in the same fiber.

During the past years, dual wavelength laser emission has been demonstrated using a co-doped Nd/Er fiber laser [7,8]. Dual laser emission in the 1µm (Nd spectral band) and 1.5µm (Er spectral band) regions has been obtained but with very low efficiency. Another possibility to obtain simultaneous emission in these spectral ranges is the use of Er/Yb co-doped fiber. In Er/Yb co-doped fiber lasers, pump photons are initially absorbed by Yb ions, and then transferred toward Er ions by cooperative cross relaxation. Yb^{3+} ion has a larger absorption cross section than Er^{3+}, and a relative immunity to self quenching. So, Er/Yb co-doping allows to achieve efficient pump absorption in a clad pumping configuration (typically several dB/m), even for a large cladding-to-core area ratio. For these reasons, Er/Yb co-doped fiber lasers have stood out as most efficient laser sources in the important "eye safe" region [9-12]. Although residual Yb co-lasing around 1µm was observed [9-11], it was considered for these applications as a parasitic effect, and efforts are made to suppress it by optimizing the core composition to achieve a quasi-total energy transfer from Yb to Er ions and by increasing intra-cavity losses at 1µm.

On the contrary, we have for this study specifically designed and fabricated an Er/Yb co-doped fiber whose core composition limits the cooperative cross relaxation between Yb and Er ions, to achieve simultaneous and balanced population inversion of both Er and Yb. This fiber was included in a standard laser configuration, and intra-cavity differential losses for both wavelengths allowed us to obtain low threshold and comparably powerful lasing lines for both Er and Yb laser emissions. The two generated beams were launched into a PPLN crystal to generate a tunable red-light by Sum Frequency Generation (SFM). The Quasi Phase

Matching (QPM) conditions were optimized over several nanometers by tuning the crystal temperature from ambient to 140°C.

2. Composition of Er/Yb co-doped fiber to ensure dual band emission

Figure 1 shows a simplified model of energy levels in the Er/Yb dual wavelength fiber laser. Because the Yb^{3+} absorption cross section at the pump wavelength (980nm) is about 10 times higher than for Er, most of the pump light is absorbed by Yb ions, which are excited to the $^2F_{5/2}$ state. In laser configuration, population inversion of Yb ions can lead to two phenomena: stimulated emission around λ_1=1.06µm, or energy transfer to the $^4I_{11/2}$ level of Er^{3+} by way of a direct dipole-dipole energy transfer process. A quick non radiative transition toward the $^4I_{13/2}$ state induces a population inversion and a laser emission at λ_2=1.55µm.

First, the total rare earth concentration was kept low (about 1000ppm), to ensure efficient population inversion with a limited available pump power (500mW). Despite this low active ion concentration, we achieved an efficient pump absorption of about 3dB/m in a clad pumped configuration, thanks to the low cladding-to-core area ratio close to 25 and the D-shaped inner cladding design. Then, we determinated a chemical composition of the core leading to a limited energy transfer, in order to achieve a balanced stimulated emission from both rare earth ions. For this purpose, two phenomena have been specifically taken into account: ion clustering and back transfer from Er^{3+} to Yb^{3+}. Both Er and Yb ions, which have the same ionic radius, exhibit a low level of solubility in a silica host, leading to clustering effect. Moreover, the proximity of both ions can enhance the energy transfer between ions until Yb lasing extinction. We included Al_2O_3 at the same time with rare earth ions by solution-doping method in order to increase the amount of ion hosts in the silica matrix. The Al_2O_3 content was estimated around 1 mol% (i.e. 20000 mol ppm of Al atoms), therefore the $[Al]/([Er^{3+}]+[Yb^{3+}]$ ratio was ~20, high enough to decrease the parasitic clustering effect [13] and hence limit the energy transfer between rare earth ions. Moreover, it was experimentally shown [10] that single or dual wavelength operation of a co-doped Er/Yb fiber laser can be chosen by adjusting the Phosphorus concentration. Indeed, the back transfer from Er^{3+} to Yb^{3+} depends on the $^4I_{11/2}$ level lifetime of the Er^{3+}: as the lattice maximum phonon energies are higher in phosphates than in silica (1325cm^{-1} compared with 1190cm^{-1}), co-doping the silica host with P_2O_5 can significantly delay this backflow. So, fibers used for 1.55µm high power applications require high P_2O_5 core concentration with typical values of about 10-20 mol% [14]. On the contrary, in the aim to obtain comparable population inversions in both Yb and Er gain bandwidths, we limited this Phosphorus concentration to a low value of about 3 mol%. Absolute and relative rare earth concentrations were respectively [Er]+[Yb]=1000ppm and [Er]/[Yb]=2.

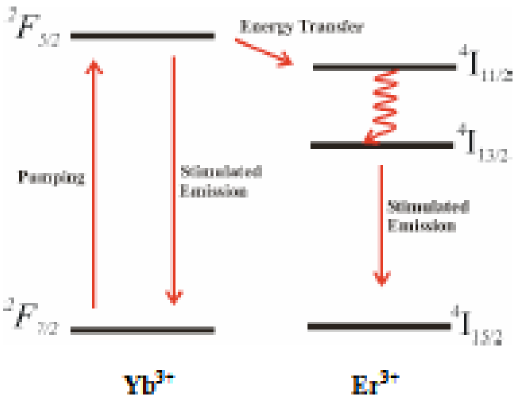

Fig. 1. Simplified model of energy levels in an Er/Yb laser.

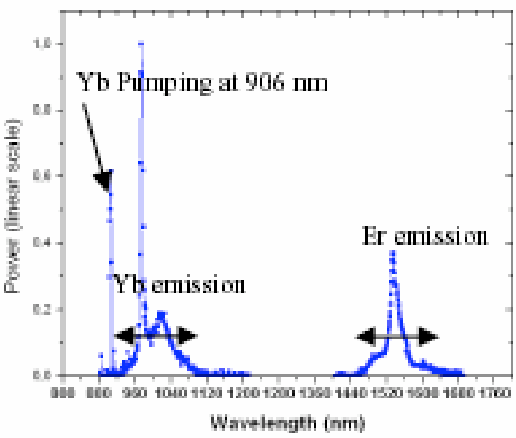

Fig. 2. Spectrum emitted transversally from the Er3+ /Yb3+ fiber under an excitation of 150mW at 906nm.

To verify that nearly equal gain was available on both Er and Yb bands, we experimented selective excitation of Yb ions into the co-doped fiber under 150mW at 906nm from a Ti:sapphire laser (core pumping). Spectral analysis was carried out with a monochromator on the fiber side through fiber cladding, in order to prevent any parasitic distortion or amplification of the analyzed signal due to the signal propagation in the fiber. The measured spectrum shown on Fig. 2 highlights the limited energy transfer between both ions: although only the Yb ions were excited, emission in the Er band was also detected. Emission at 980nm in the Ytterbium band is not significant because it corresponds to the pump radiation in the final fiber laser configuration. So, as expected, the gains on both ion bands are roughly the same with predominance in the Er band. This weak difference between gain levels in the two bands, which could lead to an increase of the Yb lasing threshold, will be compensated by increasing intra-cavity losses at 1.55µm.

3. Experimental Set-up

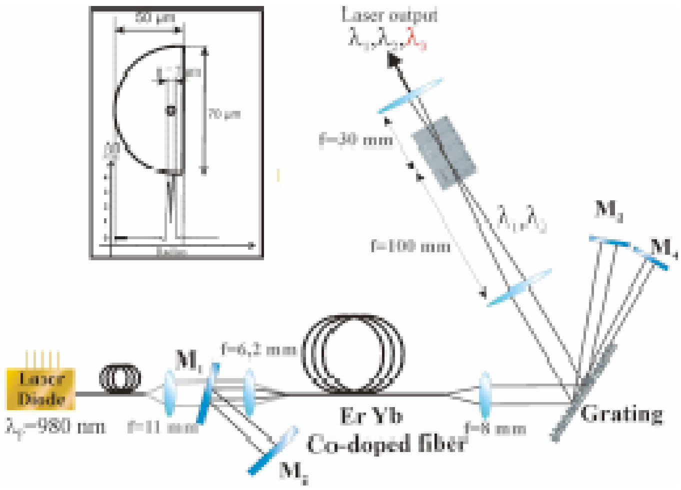

Fig. 3. Multi-wavelength laser set up; M$_1$: Dichroic mirror, T_{max} @ λ_p=980 nm and R_{max} @ λ_1=1.06 µm. M$_2$ and M$_3$: Mirrors R_{max} @ λ_1=1.06 µm, M$_4$: Mirror R_{max} @ λ_2=1.55 µm. λ_1, λ_2, λ_3, are respectively 1550nm, 1064nm, 631nm. Inset: Geometrical parameters and refractive index profile of the co-doped fiber.

The multi-wavelength fiber laser device is depicted in Fig. 3. Clad pumping configuration was chosen to allow the use of high power laser diode. However in this demonstration, only 450mW of the pump power at 980nm is launched in the inner cladding of the fiber from the multimode laser diode. The laser source is built around a 5m long Er/Yb co-doped fiber amplifier the opto-geometrical parameters of which are shown in the inset of Fig. 3. The Er/Yb co-doped preform is made by the standard MCVD process, and is side polished in order to obtain a D-shaped inner cladding ensuring chaotic propagation and good absorption of the pump wave. The fiber is coated with a low refractive index polymer providing an inner cladding numerical aperture of about 0.4. The core diameter (7µm) and the low refractive index difference between core and cladding (Δn=0.004) ensure single-mode propagation at both wavelengths (λ_1=1.06µm and λ_2=1.55µm) in the co-doped fiber. Each end of this fiber is angle cleaved in order to prevent any Fresnel reflection in the cavity.

At the output end of the fiber, the laser beam is collimated and sent on an intra-cavity diffraction grating (1200 grooves/mm). The wavelength tunability is obtained by rotating independently the mirrors M$_3$ and M$_4$ which close the cavity for radiations at λ_1 (Yb spectral band) and λ_2 (Er spectral band) respectively. The energy transfer from Yb toward Er ions leads to a noticeably higher gain level in the Er ion band. This gain difference is compensated by adjusting the Q-factor of the cavity at each wavelength (M$_2$-M$_3$ and M$_2$-M$_4$). This adjustment is achieved by the dichroic mirror M$_1$ which exhibits a high transmission at 0.98µm and a differential reflectivity at λ_1 and λ_2 (100% @ λ_1 = 1.06µm and 30% @ λ_2 = 1.55µm). The cavity back mirror (M$_2$) is a broadband metallic mirror.

The zero-order of the grating serves as an output coupler, and is launched in a 10mm long PPLN crystal of poling period 11.4µm. Thanks to the intracavity grating, the output beams at λ_1 and λ_2 have a linear S-polarization which leads to a maximum conversion efficiency in the PPLN crystal.

4. Results

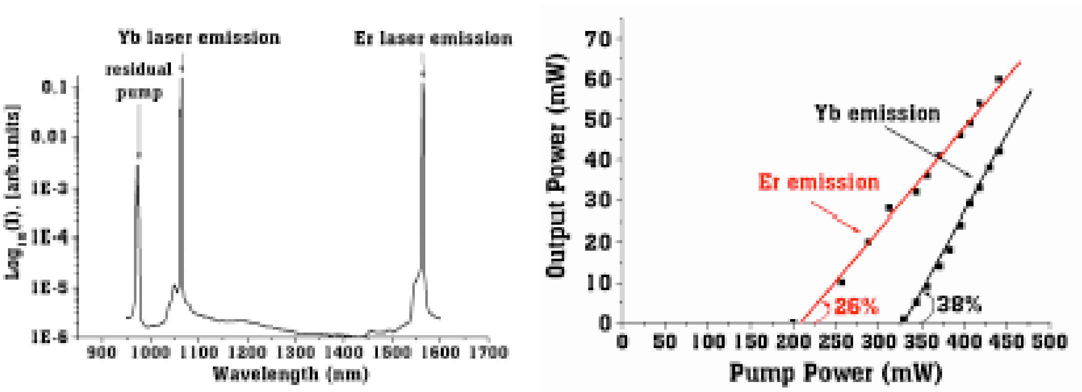

Fig. 4. (left) Emission spectrum of the dual wavelength co-doped Er/Yb fiber laser (right) Output powers at λ_1 and λ_2 versus pump power.

The specific design of the co-doped fiber allows simultaneous laser emission at both wavelengths λ_1 and λ_2, as shown on Fig. 4 (left).The two lasing lines exhibit a good spectral purity, with spectral full width at half maximum intensity lower than 0.1nm for both wavelengths, making efficient frequency conversion in non linear crystal possible. The fiber laser exhibits two distinct thresholds at both wavelengths (200mW at 1560nm, 325mW at 1064nm, see Fig. 4 (right)) depending on the cavity losses (Q cavity factor) and on the gain at 1.06µm and 1.55µm including energy transfer between doping ions. In this two-wavelength fiber laser, pump power is shared between both Yb and Er ions, which explains the measured moderate slope efficiencies, respectively 38% and 26% at λ_1 and λ_2. Under a maximum pump level of 450mW, 42mW at λ_1 and 60mW at λ_2 are measured at the laser output. By tilting the mirror M_3, the laser emission in the Yb gain bandwidth has been tuned over 48 nm, from 1028 nm to 1076 nm. The second emitted radiation has been tuned by means of the mirror M_4 between 1532nm and 1557nm.

The fundamental Gaussian beams at the fiber output are collinear, with respective radiuses equal to 3.9µm and 5.8µm at λ_1 and λ_2. They are focused with an achromatic lens (100 mm focal length) in the thermally controlled PPLN crystal. The waist radiuses of λ_1 and λ_2 beams are respectively equal to ω_{01}=49µm and ω_{02}=72µm and they interact over 7mm in the non linear medium. This crystal is designed to generate sum frequency at λ_s=631nm from λ_1=1.064µm and λ_2=1.55µm at 84°C (see Fig. 5, left). The temperature can be tuned from ambient to 140°C with an accuracy of 1°C. Incident and converted signals are characterized at the crystal output.

In the following experiments, we have demonstrated wide band conversion from IR to red spectral range by SFM in this PPLN, taking advantage of the Er/Yb co-doped fiber laser tunability. First, we have plotted (Fig. 5) temperature dependent quasi phase matching conditions in the non linear crystal, using Sellmeïer expansions [15].

For a PPLN crystal temperature fixed to 84°C, we checked that for a λ_2 variation of 30nm (1530nm, 1560nm), QPM conditions lead to a limited SFM wavelength variation of about 1nm. So, to obtain maximum tunability in the red spectral range, we fixed λ_2 at 1550 nm, and tuned λ_1 from 1054nm to 1074.5nm, while varying the PPLN crystal temperature from 25°C to 140°C (maximum temperature available with our oven).

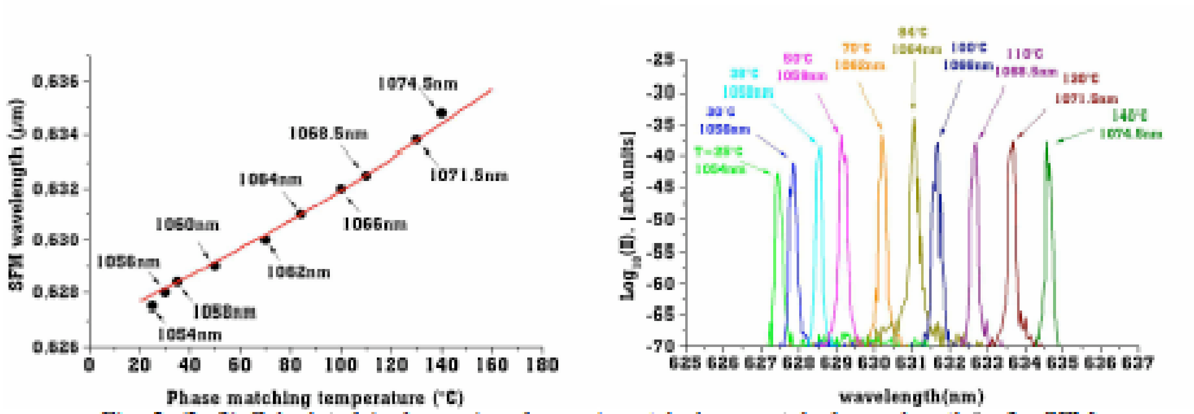

Fig. 5. (Left) Calculated (red curve) and experimental phase matched wavelength λ_1 for SFM with λ_2 fixed to 1550nm versus the PPLN crystal temperature. (Right) Tunable measured visible spectrum in the red region at the PPLN output for λ_1 and T_{PPLN} variable, λ_2 fixed to 1550nm.

So, we have generated tunable red emission from 627.5nm (λ_1=1054nm, λ_2=1550nm, T_{PPLN}=25°C) to 634.5nm (λ_1=1074.5nm, λ_2=1550nm, T_{PPLN}=140°C). Experimental spectra are given on Fig. 5 (right).

A maximum of 0.14 mW of power at 631nm (λ_1=1064nm, λ_2=1550nm, T_{PPLN}=84°C) was experimentally measured with two fundamental waves of moderate power (respectively 42mW at λ_1 and 60mW at λ_2). The measured value leads to an IR to red conversion efficiency of 0.14%. We have to note that the non-linear crystal has no antireflection coating. Figure 6 illustrates the relative powers between red and IR signals at the output of the non-linear crystal. Of course, this poor conversion efficiency, limited by the cw regime, will be easily improved by increasing power density using pulsed regime.

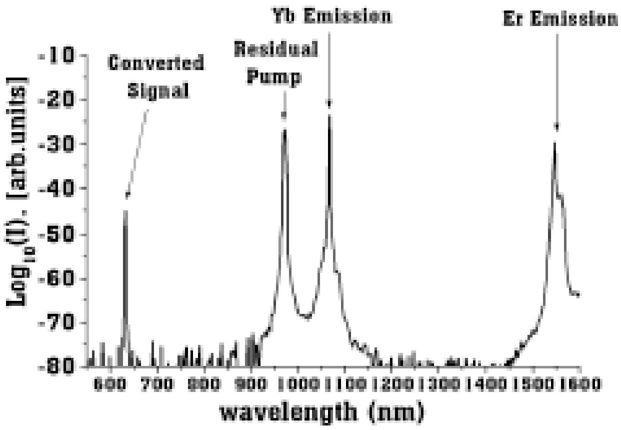

Fig. 6. Spectral power density measured at the PPLN crystal output.

5. Conclusion

We have designed and manufactured a co-doped Er/Yb fiber to avoid the total energy transfer from the Yb ions to the Er ones. In a three mirror laser resonator, this fiber has delivered tunable and quasi-independent dual infrared wavelengths in the continuous wave regime. Rare earth ions in silica matrix of fiber make possible a large spectrum emission range and so tunable frequency generation in the visible by nonlinear frequency mixing. In that way, the output beam with both IR wavelengths was focused in a PPLN crystal to generate tunable emission in the red from 627.5nm to 634.5nm. The low conversion efficiency of the non linear SFM process of 0.14% can be easily improved by increasing power density with higher pump power and pulsed regime. The use of multi-doped fiber combined with frequency conversion in non linear crystal represents a promising way for reaching tunable multi-wavelength laser emission.